



Search for contact interactions and large extra dimensions in the dilepton mass spectra from proton-proton

CMS Collaboration ; Canelli, Maria Florencia ; Kilminster, Benjamin ; Aarrestad, Thea K ; Brzhechko, Danyyl ; Caminada, Lea ; de Cosa, Annapaoloa ; Del Burgo, Riccardo ; Donato, Silvio ; Galloni, Camilla ; Hreus, Tomas ; Leontsinis, Stefanos ; Mikuni, Vinicius Massami ; Neutelings, Izaak ; Rauco, Giorgia ; Robmann, Peter ; Salerno, Daniel ; Schweiger, Korbinian ; Seitz, Claudia ; Takahashi, Yuta ; Wertz, Sebastien ; Zucchetta, Alberto ; et al

Abstract: A search for nonresonant excesses in the invariant mass spectra of electron and muon pairs is presented. The analysis is based on data from proton-proton collisions at a center-of-mass energy of 13 TeV recorded by the CMS experiment in 2016, corresponding to a total integrated luminosity of 36 fb^{-1} . No significant deviation from the standard model is observed. Limits are set at 95% confidence level on energy scales for two general classes of nonresonant models. For a class of fermion contact interaction models, lower limits ranging from 20 to 32 TeV are set on the characteristic compositeness scale Λ . For the Arkani-Hamed, Dimopoulos, and Dvali model of large extra dimensions, the first results in the dilepton final state at 13 TeV are reported, and values of the ultraviolet cutoff parameter Λ_T below 6.9 TeV are excluded. A combination with recent CMS diphoton results improves this exclusion to Λ_T below 7.7 TeV, providing the most sensitive limits to date in nonhadronic final states.

DOI: [https://doi.org/10.1007/JHEP04\(2019\)114](https://doi.org/10.1007/JHEP04(2019)114)

Posted at the Zurich Open Repository and Archive, University of Zurich

ZORA URL: <https://doi.org/10.5167/uzh-180054>

Journal Article

Published Version



The following work is licensed under a Creative Commons: Attribution 4.0 International (CC BY 4.0) License.

Originally published at:

CMS Collaboration; Canelli, Maria Florencia; Kilminster, Benjamin; Aarrestad, Thea K; Brzhechko, Danyyl; Caminada, Lea; de Cosa, Annapaoloa; Del Burgo, Riccardo; Donato, Silvio; Galloni, Camilla; Hreus, Tomas; Leontsinis, Stefanos; Mikuni, Vinicius Massami; Neutelings, Izaak; Rauco, Giorgia; Robmann, Peter; Salerno, Daniel; Schweiger, Korbinian; Seitz, Claudia; Takahashi, Yuta; Wertz, Sebastien; Zucchetta, Alberto; et al (2019). Search for contact interactions and large extra dimensions in the dilepton mass spectra from proton-proton. Journal of High Energy Physics, 04:114.

DOI: [https://doi.org/10.1007/JHEP04\(2019\)114](https://doi.org/10.1007/JHEP04(2019)114)

Search for contact interactions and large extra dimensions in the dilepton mass spectra from proton-proton collisions at $\sqrt{s} = 13$ TeV



The CMS collaboration

E-mail: cms-publication-committee-chair@cern.ch

ABSTRACT: A search for nonresonant excesses in the invariant mass spectra of electron and muon pairs is presented. The analysis is based on data from proton-proton collisions at a center-of-mass energy of 13 TeV recorded by the CMS experiment in 2016, corresponding to a total integrated luminosity of 36 fb^{-1} . No significant deviation from the standard model is observed. Limits are set at 95% confidence level on energy scales for two general classes of nonresonant models. For a class of fermion contact interaction models, lower limits ranging from 20 to 32 TeV are set on the characteristic compositeness scale Λ . For the Arkani-Hamed, Dimopoulos, and Dvali model of large extra dimensions, the first results in the dilepton final state at 13 TeV are reported, and values of the ultraviolet cutoff parameter Λ_T below 6.9 TeV are excluded. A combination with recent CMS diphoton results improves this exclusion to Λ_T below 7.7 TeV, providing the most sensitive limits to date in nonhadronic final states.

KEYWORDS: Beyond Standard Model, Hadron-Hadron scattering (experiments)

ARXIV EPRINT: [1812.10443](https://arxiv.org/abs/1812.10443)

Contents

1	Introduction	1
2	The CMS detector	3
3	Lepton reconstruction and event selection	4
4	Background and signal estimation	5
5	Systematic uncertainties	6
6	Mass spectra and statistical analysis	8
7	Summary	10
	The CMS collaboration	17

1 Introduction

Nonresonant enhancements of the production rate of high invariant mass lepton pairs in proton-proton (pp) collisions have been predicted in several models [1, 2] of phenomena beyond the standard model (SM). In these models, the differential cross section for the production of charged lepton pairs can be described by the equation:

$$\frac{d\sigma_{X\rightarrow\ell\ell}}{dm_{\ell\ell}} = \frac{d\sigma_{\text{DY}}}{dm_{\ell\ell}} + \eta_X \mathcal{I}(m_{\ell\ell}) + \eta_X^2 \mathcal{S}(m_{\ell\ell}), \quad (1.1)$$

where $m_{\ell\ell}$ is the invariant mass of the two leptons, $d\sigma_{\text{DY}}/dm_{\ell\ell}$ is the SM Drell-Yan (DY) differential cross section, η_X is a model specific form factor, and the signal contribution terms are separated into an interference term (\mathcal{I}) and a pure signal term (\mathcal{S}). Interference between new physical processes and the SM DY process is possible when the new process acts on the same initial state and yields the same final state. For the analysis presented in this paper we consider two nonresonant scenarios: a contact interaction arising from the existence of fermion substructure; and the effects of virtual spin-2 gravitons as predicted by models with large extra dimensions.

The existence of three generations of quarks and leptons has led to speculation [1] that these particles may be composed of more fundamental constituents, which have been called “preons”. The preons would account for the properties of quarks and leptons via a new strong gauge interaction, analogous to the color interaction in quantum chromodynamics (QCD). Below a given energy scale Λ , the main effect of this QCD-like interaction is to bind the preons into singlet states with respect to the new gauge interaction. Given the

present limits on the substructure of quarks and leptons, it is expected that Λ would be on the order of at least several TeV. For parton interactions at a center-of-mass energy \sqrt{s} much lower than Λ , the presence of preon bound states would result in a flavor-diagonal “contact interaction” (CI) [3]. Assuming quarks and leptons share common constituents, the Lagrangian for the CI process $q\bar{q} \rightarrow \ell\ell$, where ℓ is a charged lepton, can be expressed as

$$\mathcal{L}_{q\ell} = \frac{g_{\text{contact}}^2}{\Lambda^2} \left[\eta_{LL}(\bar{q}_L \gamma^\mu q_L)(\bar{\ell}_L \gamma_\mu \ell_L) + \eta_{RR}(\bar{q}_R \gamma^\mu q_R)(\bar{\ell}_R \gamma_\mu \ell_R) \right. \\ \left. + \eta_{LR}(\bar{q}_L \gamma^\mu q_L)(\bar{\ell}_R \gamma_\mu \ell_R) + \eta_{RL}(\bar{q}_R \gamma^\mu q_R)(\bar{\ell}_L \gamma_\mu \ell_L) \right], \quad (1.2)$$

where $q_L = (u, d)_L$ is a left-handed quark doublet; q_R represents a sum over the right-handed quark singlets (u- and d-type); and ℓ_L and ℓ_R are the left- and right-handed leptons, respectively. By convention, $g_{\text{contact}}^2/4\pi = 1$ and the helicity parameters η_{ij} are taken to have unit magnitude. The compositeness scale, represented by Λ , is potentially different for each of the individual terms in the Lagrangian. Therefore, the individual helicity currents for “left-left” (LL), “right-right” (RR), and the combination of “left-right” (LR) and “right-left” (RL) in eq. (1.2), together with their scales (Λ_{LL} , Λ_{RR} , and Λ_{LR}), are considered separately in this search, and in each case all other currents are assumed to be zero. The combination of LR and RL is referred to simply as LR throughout the paper. A given η_{ij} can be related to the form factor in the differential cross section in eq. (1.1) by

$$\eta_X = -\frac{\eta_{ij}}{\Lambda_{ij}^2}, \quad (1.3)$$

where both constructive ($\eta_{ij} < 0$) and destructive ($\eta_{ij} > 0$) interference with DY processes are possible.

Theories extending the SM with additional dimensions have been studied extensively [4]. The model with large extra dimensions developed by Arkani-Hamed, Dimopoulos, and Dvali (ADD) [2] describes quantum gravity as an effective field theory. It has the potential to solve, at the TeV scale, the so-called “hierarchy problem”, which arises from the large difference between the Higgs boson mass [4] and the energy scale, referred to as the Planck mass M_{Pl} , at which gravity is expected to become strong. This is achieved via an extension of spacetime by n additional compactified spatial dimensions of size L . In the ADD model, all SM particles are confined to the four-dimensional subspace (the brane), while gravity can propagate to all $D = n + 4$ dimensions (the bulk). If L is sufficiently large, the D -dimensional fundamental Planck mass M_D , which is related to M_{Pl} in three dimensions by

$$M_D^{2+n} = M_{Pl}^2/L^n, \quad (1.4)$$

can then be probed at the TeV scale. The aforementioned compactification of the additional dimensions results in periodic boundary conditions, and thus a quasi-continuous spectrum of Kaluza-Klein graviton modes. As the interaction scale increases, more graviton modes are excited, leading the ADD model to predict a nonresonant excess of lepton pairs at high dilepton masses originating from the decay of virtual gravitons. These processes can be characterized by the single energy cutoff scale Λ_T in the Giudice-Rattazzi-Wells (GRW) convention [5], the string scale M_S in the Hewett convention [6], or the number of

additional dimensions n in conjunction with M_S in the Han-Lykken-Zhang (HLZ) convention [7]. The generic form factor η_X is replaced by η_G in eq. (1.1), which depends on the chosen convention:

$$\text{GRW:} \quad \eta_G = \frac{1}{\Lambda_T^4}; \quad (1.5)$$

$$\text{Hewett:} \quad \eta_G = \frac{2}{\pi} \frac{\lambda}{M_S^4} \quad \text{with } \lambda = \pm 1; \quad (1.6)$$

$$\text{HLZ:} \quad \eta_G = \begin{cases} \ln(M_S^2/\hat{s}) \frac{1}{M_S^4} & \text{for } n = 2 \\ \frac{2}{n-2} \frac{1}{M_S^4} & \text{for } n > 2. \end{cases} \quad (1.7)$$

Of the three, only the Hewett convention allows both constructive and destructive interference with the SM DY process, but in this paper only the constructive case ($\Lambda = +1$) is considered. Relative to CI models, interference with DY in the ADD model is more limited as the production of virtual gravitons is dominated by gluon-induced processes. Both Λ_T and M_S function as ultraviolet (UV) cutoff parameters, indicating the energy scale up to which the effective field theory provides reliable predictions. Beyond this point, a description of quantum gravity becomes necessary to accurately describe particle interactions.

The analysis presented in this paper focuses on dilepton (electron or muon) events produced in pp collisions at a center-of-mass energy of 13 TeV at the CERN LHC. The data sample was recorded by the CMS experiment in 2016, and corresponds to an integrated luminosity of 35.9 (36.3) fb⁻¹ for the electron (muon) channel.

For both the CI and ADD models, this paper extends previous results from CMS at 8 TeV [8], and complements the recent CMS search at 13 TeV for resonant phenomena [9] in dilepton final states. Additional constraints on these models from diphoton and dijet final states have been reported by CMS [10, 11]. The ATLAS Collaboration has presented similar results for these models in the dilepton final state, the most recent using data at 8 TeV [12] for the ADD model and at 13 TeV [13] for the CI model.

2 The CMS detector

The central feature of the CMS detector is a superconducting solenoid providing an axial magnetic field of 3.8 T and enclosing a silicon strip and pixel tracker, an electromagnetic calorimeter (ECAL), and a hadron calorimeter (HCAL). The silicon tracker measures charged particles within the pseudorapidity range $|\eta| < 2.5$. The ECAL and HCAL, each composed of a barrel and two endcap sections, extend over the range $|\eta| < 3$, while a forward calorimeter encompasses $3 < |\eta| < 5$.

The muon detection system covers $|\eta| < 2.4$ with up to four layers of gas-ionization chambers installed outside the solenoid and sandwiched between the layers of the steel flux-return yoke. Additional detectors and upgrades of electronics were installed before the beginning of the 13 TeV data collection period in 2015, yielding improved reconstruction performance for muons relative to the 8 TeV data collection period in 2012. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in ref. [14].

The CMS experiment has a two-level trigger system [15]. The level-1 (L1) trigger, composed of custom hardware processors, selects events of interest using information from the calorimeters and muon detectors; the software based high-level trigger (HLT) then uses the full event information, including that from the inner tracker, to select the events that are recorded for analysis.

3 Lepton reconstruction and event selection

A detailed description of the reconstruction and selection of electron and muon pairs used in this analysis can be found in ref. [16] and is briefly summarized below.

Candidate events in the electron channel are selected first by the L1 trigger, which requires two energy deposits (clusters) in the ECAL with transverse momentum $p_T > 24$ (17) GeV, respectively. A suite of L1 trigger algorithms, requiring single, highly energetic calorimeter clusters, has also been used to select events for this analysis to guard against potential inefficiencies of the primary trigger. The HLT then requires that both electron candidates have $p_T > 33$ GeV and pass loose identification criteria.

Electron candidates are reconstructed by matching tracks originating from the nominal interaction point with ECAL energy clusters. These clusters include the energy coming from bremsstrahlung photons. The electron candidates are required to have $p_T > 35$ GeV and cluster pseudorapidity $|\eta_C| < 1.44$ (barrel) or $1.57 < |\eta_C| < 2.50$ (endcap). The intermediate region is excluded because of the reduced reconstruction quality of clusters in the overlap of the barrel and endcap components of the ECAL.

Furthermore, the candidates are required to pass a specialized selection, optimized for high-energy electrons [17], ensuring that the electron track is well reconstructed, that the transverse size of the ECAL cluster is consistent with that of an electron, and that there is minimal energy leakage into the HCAL. Additionally, the electron candidate must be well isolated in the calorimeter and the tracker, within a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$, where ϕ is the azimuthal angle.

For events in which two or more electrons meet all of the aforementioned requirements, all possible electron pair candidates are created. For each of the pair candidates, at least one of the electrons is required to be in the barrel region. Should more than one pair pass the selection, the pair with the largest p_T sum is used.

In the muon channel, events are selected by the L1 trigger requiring two muons, at least one of which must have transverse momentum $p_T > 22$ GeV. The HLT requires that at least one of the muons have $|\eta| < 2.4$ and $p_T > 50$ GeV. A separate HLT algorithm, with a threshold of $p_T > 27$ GeV, is used to select a large event sample at the Z boson peak ($60 < m_{\mu\mu} < 120$ GeV), which is used to derive the normalization of the simulated backgrounds.

Muon candidates are required to have matching segments in the tracker and the muon system. Further selection requirements are applied offline [8], among which are the requirements that muon candidates must have $|\eta| < 2.4$ and $p_T > 53$ GeV. Isolated muon candidates are selected by requiring that the scalar sum of the transverse momenta of all tracks within a cone of $\Delta R < 0.3$ around the muon must be less than 10% of the muon p_T . A dedicated algorithm [18] is used for the reconstruction of muons with $p_T > 200$ GeV,

which accounts for radiative energy losses due to interactions of the highly energetic muons with the detector material.

Muon pairs are formed from oppositely charged muons, with one of the muons required to match the muon that triggered the event. A χ^2 fitting method is used to ensure that the muon candidate tracks are compatible with originating from a common vertex. The three-dimensional angle between the two muon candidates is required to be less than $\pi - 0.02$, to suppress muons originating from cosmic rays. If more than one pair of muons pass all aforementioned requirements, the pair with the highest p_T sum is chosen.

The search region ($m_{\ell\ell} > 400$ GeV) is divided into two categories, depending on the location of the two leptons. Events where both leptons are in the barrel region are called barrel-barrel (BB), while events where at least one lepton is in the endcap are called barrel-endcap (BE). For the electron channel, events where both electrons are in the endcap region are ignored. The efficiency to trigger, reconstruct, and select a lepton pair with invariant mass around 1 TeV is 69 (65)% in the electron channel for BB (BE) events, while it is about 93% for events in the muon channel.

4 Background and signal estimation

The primary SM production channel for lepton pairs in this analysis is the DY process. It is simulated with POWHEG v2 [19–24] at next-to-leading-order (NLO) in perturbative QCD, using the NNPDF 3.0 [25] set of parton distribution functions (PDFs) and PYTHIA 8.205 [26] for parton showering and hadronization. A mass-dependent correction factor is applied in order to reach next-to-next-to-leading order (NNLO) accuracy in perturbative QCD, and to account for weak effects at NLO, as well as pure quantum electrodynamics effects. This factor is derived as the ratio of the cross sections calculated by FEWZ 3.1b2 [27] to those calculated with POWHEG, using a combination of PDFs from PDF4LHC15 [28–30] and the LUX [31] PDF set for the photon PDFs. This correction factor also accounts for photon-induced processes [32, 33], stemming from $\gamma\gamma$ initial states. The effect of these processes does not exceed 5% for masses up to 2 TeV and reaches 15–20% above 5 TeV [33]. The simulation of the detector response is performed by GEANT4 [34].

Other background processes yielding lepton pairs in the signal region are the production of top quark pairs, single top quarks via Wt production, and production of W boson pairs (WW). These processes are simulated with POWHEG [19–24], using NNPDF 3.0 as the PDF set and a mix of PYTHIA 8.205 and 8.212 for showering and hadronization. The top quark pair production cross section is calculated up to NNLO, including leading-log effects for soft gluon resummation, with TOP++ 2.0 [35], while the Wt cross section has been calculated up to next-to-next-to-leading log accuracy [36]. Cross sections for other processes have been calculated up to NNLO with MCFM 6.6 [37–40].

In addition to the WW background produced with POWHEG, WZ and ZZ production is simulated inclusively at leading order (LO) with PYTHIA, using the NNPDF 2.3 [41] PDF set. Production of τ lepton pairs through the DY process, which then decay to electron or muon pairs, is simulated at NLO with MADGRAPH5_aMC@NLO 2.2.2 [42], using the NNPDF 3.0 PDF set and PYTHIA for showering and hadronization.

The overall yield from these processes is then normalized to the data in the control region around the Z boson peak. Background from events containing jets that are misreconstructed as isolated leptons, is estimated from data using event samples enriched in QCD multijet events, as described in ref. [8]. The contribution of this background to the overall event sample is between 1–3%.

Each signal model, including interference with the DY process, is simulated at LO using NNPDF 2.3 and PYTHIA 8.212 and 8.205 for the CI and ADD samples, respectively. A dedicated PYTHIA DY sample is produced with the same generator settings and subtracted from the signal samples to obtain the respective signal yields. No higher-order correction factor is applied to the signal samples of the CI model; for the ADD model, a mass-independent NLO correction factor of 1.3 is used. While NNLO QCD predictions show that this correction factor can be as large as 1.6 [43], and that it always exceeds 1.3 in the considered dilepton mass range, NLO electroweak corrections are not taken into account. This motivates choosing the conservative value of 1.3, which also allows a direct comparison to previous results [8].

To account for the effects of additional pp interactions within the same or nearby bunch crossings (“pileup”), additional minimum bias events are overlaid on the simulated events. The simulated events are scaled to match the recorded luminosity, using the cross sections obtained as described above, and then reweighted so that their pileup distribution matches the one observed in the data.

5 Systematic uncertainties

A summary of the systematic uncertainties in the SM background estimates is found in table 1, and brief descriptions of their determination are given below. For each source, the corresponding relative uncertainty in the event yield is given separately for the electron and muon channels. To illustrate the mass-dependent nature of some of the uncertainties, values are shown for two different invariant mass thresholds. All of the mass-dependent uncertainties listed in table 1 affect both the total number of events and the shape of the invariant mass distribution.

The efficiency of triggering, reconstructing, and selecting electrons is measured in simulated DY events and validated using data at the Z boson peak. The uncertainty in the electron energy scale of 2 (1)% in the barrel (endcap) region has been used to derive the resulting uncertainty in the event yield.

The efficiency of the single-muon trigger to identify either of the two muons in the event has been measured using a sample of Z boson candidate events, and is found to be independent of mass. Uncertainty in the reconstruction and selection efficiency for muons leads to a corresponding uncertainty in event yield. The uncertainty in muon efficiency, as a function of p_T and η , is determined from differences between data and simulation. Because a potential bias in the muon p_T measurement may result in a bias in the dimuon mass scale, the muon curvature (q/p_T , where q is the electric charge of the muon) distribution in data is compared to that obtained from simulation for different η and ϕ ranges. The measured bias is consistent with zero, and, along with the corresponding uncertainty, is propagated to

Uncertainty	Electrons		Muons	
	$m_{ee} > 2 \text{ TeV}$	$m_{ee} > 4 \text{ TeV}$	$m_{\mu\mu} > 2 \text{ TeV}$	$m_{\mu\mu} > 4 \text{ TeV}$
Electron trigger + selection efficiency BB (BE)	6 (8)%		—	—
Electron energy scale BB (BE)	12.0 (6.7)%	21.7 (11.0)%	—	—
Muon trigger efficiency BB (BE)	—	—	0.3 (0.7)%	
Muon ID efficiency BB (BE)	—	—	0.8 (4.6)%	1.7 (7.6)%
Muon p_T resolution BB (BE)	—	—	0.8 (1.4)%	1.5 (2.3)%
Muon p_T scale BB (BE)	—	—	0.8 (2.8)%	4.1 (12.1)%
$t\bar{t}$ /diboson cross section	7%		7%	
Z boson peak normalization	1%		5%	
PDF	5.7%	17.1%	5.7%	17.1%
Multijet BB (BE)	0.1 (1.3)%	0.1 (0.1)%	<0.1 (4.8)%	<0.1 (<0.1)%
Pileup reweighting BB (BE)	0.5 (0.7)%	0.4 (0.7)%	0.2 (0.1)%	0.2 (0.2)%
MC statistics BB (BE)	1.0 (1.8)%	0.7 (1.7)%	1.1 (1.3)%	1.0 (2.0)%

Table 1. Systematic uncertainties in the predicted SM yields for the electron and the muon channels, for two dilepton mass thresholds. Where noted, uncertainties are provided separately for events where both leptons are in the barrel region (BB), or where at least one of the leptons is in the endcap region (BE). Uncertainties that are mass-dependent affect both the event yield and the shape of the invariant mass distribution. The systematic uncertainties in the signal yields are largely the same as for the background, with a few exceptions as discussed in the text.

the dimuon mass to derive the uncertainty in the event yield. The muon p_T resolution and its uncertainty are determined using muons from events with Lorentz-boosted Z bosons. The uncertainty in the resolution is found to scale with p_T .

The remaining uncertainties are applicable to both the electron and muon channels. The simulated backgrounds are normalized using data at the Z boson peak, and a systematic uncertainty is assigned to cover the observed difference between data and simulation before normalization. The uncertainty in the cross section calculation of the simulated diboson and $t\bar{t}$ events is found to be a constant 7%. Uncertainty in the PDF leads to uncertainties in the simulated DY yields. The uncertainty is determined with the PDF4LHC procedure [28–30] using replicas of the NNPDF 3.0 PDF set [25]. Other uncertainties in the NNLO DY cross section, such as due to the scale of the strong coupling constant α_S , have a negligible effect on the event yields. The precision in estimating the misreconstructed jet background is limited by the amount of data at high dilepton mass, and a conservative uncertainty of 50% is assigned. The systematic uncertainty in the simulation of pileup is derived from the 5% precision on the total inelastic pp scattering cross section that is used in the procedure to reweight the simulated event samples. The cross section is varied by this uncertainty and used to reweight the simulated events, resulting in a variation in the invariant mass distribution for all simulated processes.

The systematic uncertainties in the signal yields are largely the same as for the background, with a few exceptions. The signal samples are normalized to the total integrated luminosity, rather than to the data at the Z boson peak, and the uncertainty on the luminosity measurement is 2.5% [44]. Additionally, the uncertainties due to the cross sections and jet background estimation do not apply to the simulated signal events.

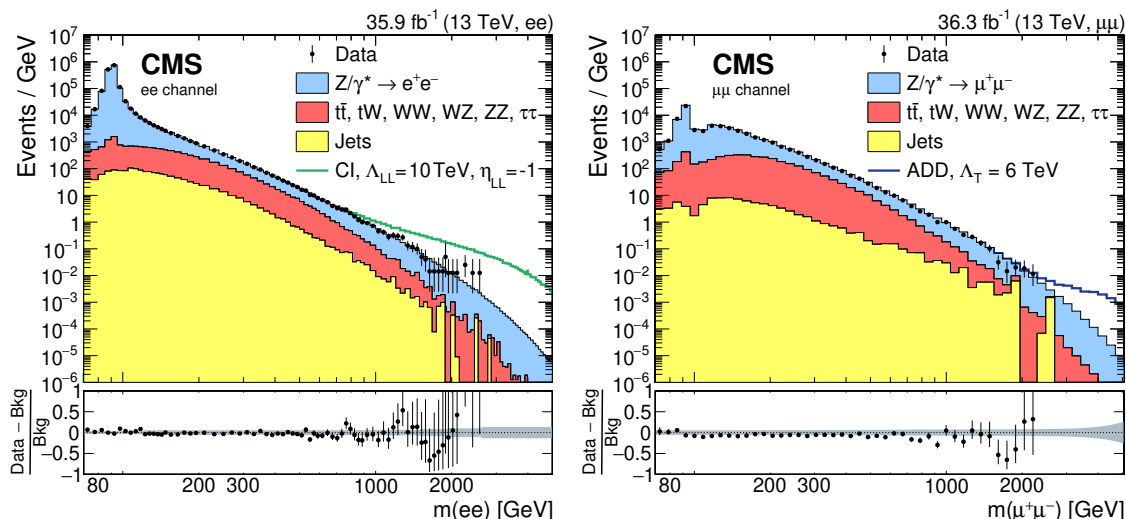


Figure 1. Electron (left) and muon (right) pair invariant mass spectra for the combined barrel-barrel and barrel-endcap event categories. Example model predictions are given for CI (left) and ADD (right). The lower panel shows the relative difference between the data and predicted background. The gray band gives the fractional uncertainty (statistical and systematic) in the prediction.

6 Mass spectra and statistical analysis

The resulting dilepton invariant mass spectra for both the electron and muon channels are shown in figure 1, inclusive of the BB and BE event categories. The simulated events are weighted by the cross section correction factors discussed in section 4. The overall simulated mass distribution is then scaled to fit the observed data yield around the Z boson peak ($60 < m_{\ell\ell} < 120$ GeV).

Results from this analysis show no significant deviation from the SM in the dilepton invariant mass spectra for either the electron or muon channel. Exclusion limits are set on the signal cross section, which are translated into limits on the respective parameters of interest for each model. These limits are calculated using Bayesian inference, utilizing the framework developed for statistically combining Higgs boson searches [45], which is based on the ROOSTATS package [46]. All uncertainties are modeled with log-normal probability density functions, while a uniform prior is used for the signal cross section.

For the CI models, two different approaches are used, depending on the signal model. A single-bin counting experiment with a lower mass threshold of 2.2 TeV, optimized for the best expected limit, is performed for the destructive interference scenarios to remove masses where the signal contribution is negative because of interference with the DY process. In the case of constructive interference, an alternative approach is used. The invariant mass spectrum is split into multiple exclusive bins, with lower bin edges of 400, 500, 700, 1100, 1900, and 3500 GeV. The last bin has an upper edge of 5000 GeV and all bins are combined in the limit calculation. Systematic uncertainties are treated as fully correlated among the bins. Expected and observed lower limits on Λ are determined from the intersection of the curves for the predicted cross section and the expected and observed upper limits on the CI

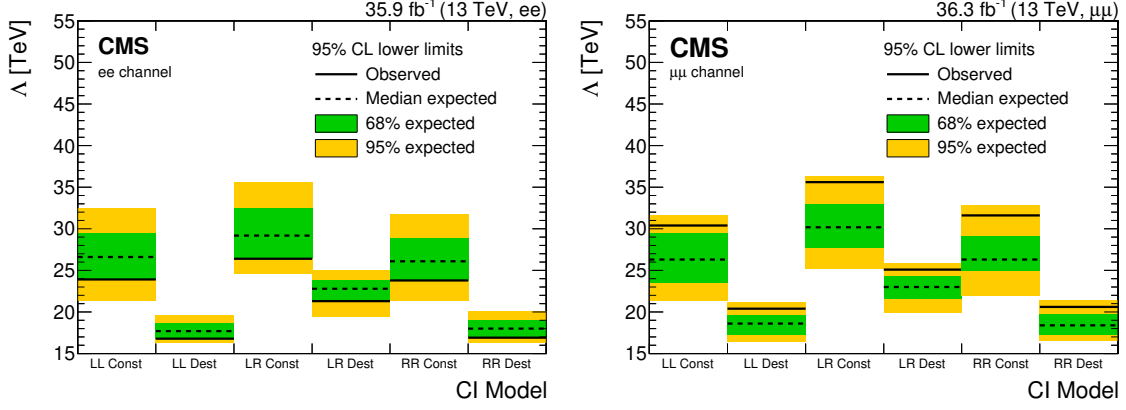


Figure 2. Dilepton exclusion limits at 95% CL on the CI scale (Λ) for the six CI models considered for the electron (left) and muon (right) channels. The limits are obtained for $m_{\ell\ell} > 400$ (2200) GeV in the case of constructive (destructive) interference.

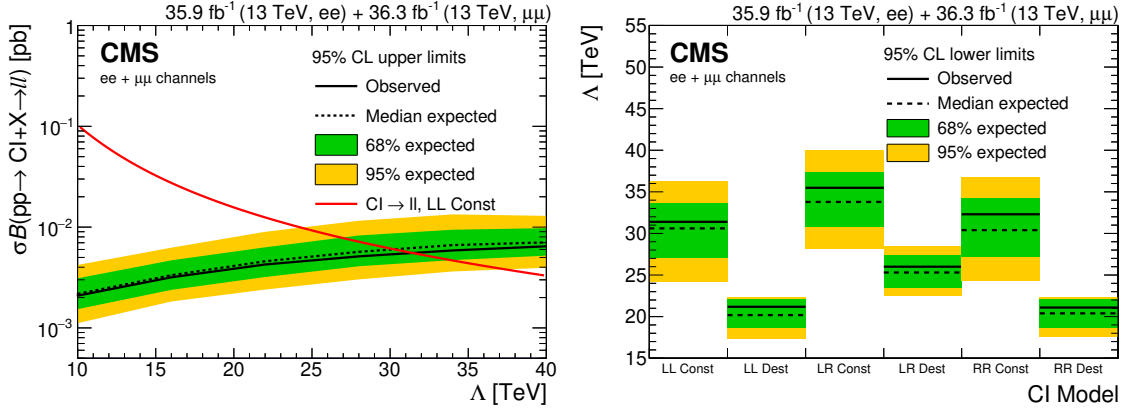


Figure 3. Combined dilepton 95% CL exclusion limits on the cross section for the left-left constructive CI model (left), and on the CI scale (Λ) for the six different CI models considered (right). The red curve in the left plot shows the theoretical cross section as a function of Λ . The limits are obtained for $m_{\ell\ell} > 400$ (2200) GeV in the case of constructive (destructive) interference.

cross section as a function of Λ . This is illustrated in figure 3 for the left-left constructive model, where the electron and muon channels are combined.

The 95% confidence level (CL) exclusion limits on the CI model parameter Λ are shown in figure 2 for the six helicity and interference models described in the introduction. The limits are more stringent for models with constructive interference than those with destructive interference. The expected limits are comparable for the electron and muon channels, which are shown separately. The observed limits are more stringent for the muon channel than for the electron channel, but are consistent within statistical fluctuation. Assuming a universal contact interaction for electrons and muons, exclusion limits can be determined for the combined data sets. These limits, shown in figure 3, range from $\Lambda_{LL} > 20$ TeV for destructive interference to $\Lambda_{RR} > 32$ TeV for constructive interference.

For the ADD model, the most sensitive part of the invariant mass spectrum, $m_{\ell\ell} > 1.8 \text{ TeV}$, is subdivided into 400 GeV wide search regions, with the final region covering the mass range between 3 TeV and Λ_T , beyond which all signal contributions are set to 0. Differentiating between the BB and BE pseudorapidity categories enhances the sensitivity as the signal is expected to be more central than the SM backgrounds. The most frequently studied parameter conventions, i.e., GRW, Hewett, and HLZ, have been considered. Figure 4 shows the 95% CL exclusion limits for the respective UV cutoff parameters in both the electron and muon channels. The combined 95% CL exclusion limit on the cross section in the GRW model is shown in figure 5, alongside the corresponding exclusion limits on the UV cutoff parameters. The lower limit on Λ_T at 95% confidence level is 6.9 TeV, which excludes a string scale M_S below 6.1 TeV in the Hewett parameter convention. In the HLZ convention, this translates to lower limits on M_S of 5.5 to 8.2 TeV, depending on the number of extra dimensions.

Utilizing the recent measurement of diphoton production [10], the overall sensitivity of the statistical analysis is further improved. Combining the data of the individual electron, muon, and photon channels, 95% CL exclusion limits are calculated using the THETA limit-setting framework [47]. As the scales of the interactions corresponding to the considered search regions, $m_{\gamma\gamma} > 500 \text{ GeV}$ and $m_{\ell\ell} > 1.8 \text{ TeV}$, differ substantially, the uncertainties are taken to be uncorrelated between the diphoton and dilepton analyses. To ensure a consistent interpretation of the exclusion limits in the combination of all three channels, no higher-order correction factor is assumed. Figure 6 shows the individual and combined limits, and the limits from the $\sqrt{s} = 8 \text{ TeV}$ dilepton measurement [8] are also shown. The highest sensitivity is given by the combination of all three channels as exhibited by the expected limits. However, an underfluctuation measured in the photon channel still results in the best observed limits. A summary of the exclusion limits on the respective UV cutoff parameters is given in table 2. The lower limit on Λ_T increases to 7.7 TeV, while the limits on M_S increase to 6.9 TeV in the Hewett convention and 6.1 to 9.3 TeV in the HLZ convention.

7 Summary

A search for nonresonant excesses in the invariant mass spectra of electron and muon pairs has been presented. The data set recorded with the CMS detector during 2016 is analyzed, corresponding to an integrated luminosity of 35.9 (36.3) fb^{-1} for the electron (muon) channel. No significant deviations from standard model expectations are observed.

A contact interaction (CI) model, taking into account both constructive and destructive interference scenarios, has been used for interpreting the experimental measurements. The 95% confidence level exclusion limits on the compositeness scale range from $\Lambda_{LL} > 20 \text{ TeV}$ for the destructive case to $\Lambda_{RR} > 32 \text{ TeV}$ for the constructive one, for the left-left and the right-right helicity currents, respectively.

For the Arkani-Hamed-Dimopoulos-Dvali (ADD) model of large extra dimensions, values of the ultraviolet cutoff parameter Λ_T (in the Giudice-Rattazzi-Wells, GRW, convention) below 6.9 TeV have been excluded at the 95% confidence level. This corresponds

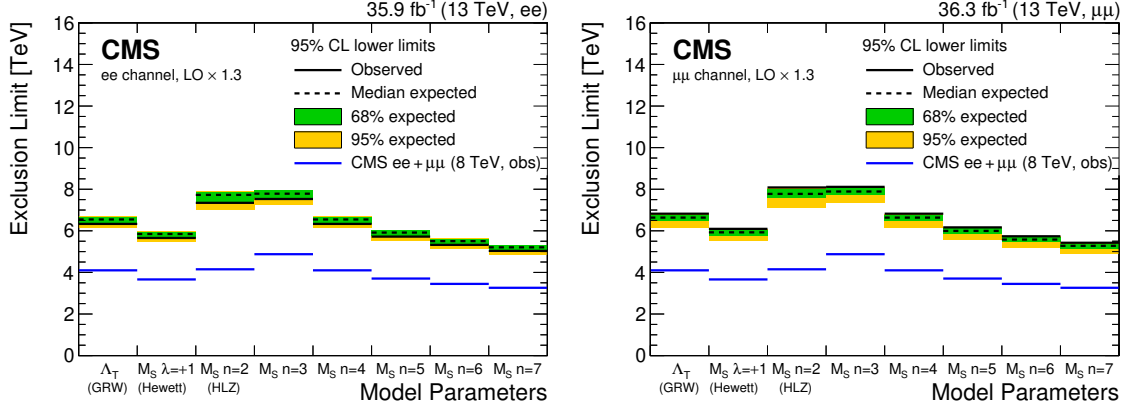


Figure 4. Exclusion limits at 95% CL on the UV cutoff for the electron (left) and muon (right) channels with $m_{\ell\ell} > 1.8$ TeV in the GRW, Hewett, and HLZ conventions for the ADD model. Signal model cross sections are calculated up to leading order and a correction factor of 1.3 is applied. The results are compared to the previous combined result from CMS [8].

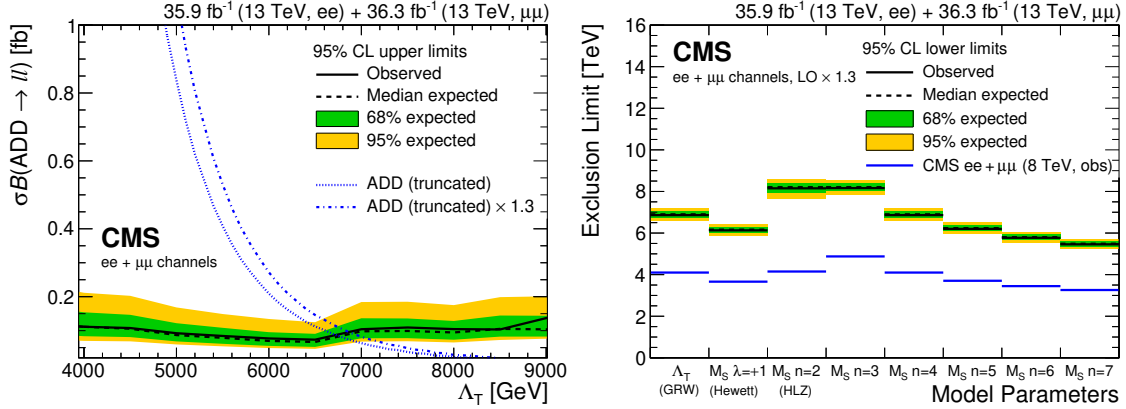


Figure 5. Combined dilepton 95% CL exclusion limit on the cross section in the GRW convention (left) and on the UV cutoff for all parameter conventions (right) with $m_{\ell\ell} > 1.8$ TeV for the ADD model. The curves labeled ADD in the left plot show the theoretical signal cross section calculated by PYTHIA, as a function of the cutoff parameter Λ_T , and signal contributions with $m_{\ell\ell} > \Lambda_T$ are set to 0. Signal model cross sections are calculated up to leading order and, where indicated by the appropriate label, a correction factor of 1.3 is applied. The results are compared to previous ones from CMS [8].

to an exclusion on the string scale M_S below 6.1 TeV in the Hewett convention; in the Han-Lykken-Zhang (HLZ) convention, lower limits are set on M_S that range from 5.5 to 8.2 TeV, depending on the number of extra dimensions. When combined with the results from the latest CMS diphoton analysis [10], these limits improve to 7.7 TeV (GRW), 6.9 TeV (Hewett), and the range 6.1 to 9.3 TeV (HLZ), respectively.

The results presented here for the CI and ADD models improve on previous CMS results at $\sqrt{s} = 8$ TeV in the dilepton final state [8]. The CI limits on Λ are compatible with the dilepton results reported by the ATLAS Collaboration [12, 13]. However, an exact

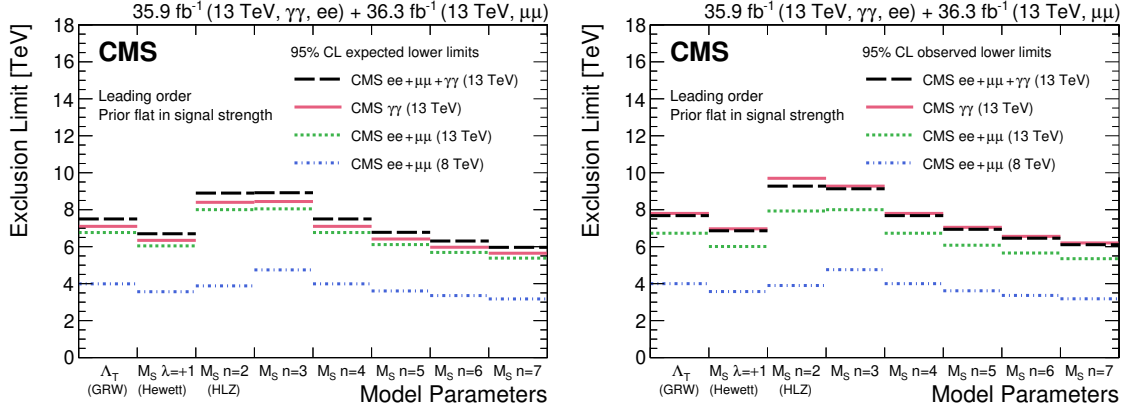


Figure 6. Individual and combined dilepton (this analysis) and diphoton [10] 95% CL expected (left) and observed (right) exclusion limits as a summary of all parameter conventions for the ADD model. Signal model cross sections are calculated up to leading order. The dilepton limits from the $\sqrt{s} = 8$ TeV measurement [8] are also shown.

Order	GRW	Hewett	HLZ					
	$\Lambda_{\text{T}}[\text{TeV}]$	$M_{\text{S}}[\text{TeV}]$	$M_{\text{S}}[\text{TeV}]$					
	$\lambda = +1$	$n = 2$	$n = 3$	$n = 4$	$n = 5$	$n = 6$	$n = 7$	
ee for $m_{\text{ee}} > 1.8 \text{ TeV}$								
LO	6.1 (6.4)	5.5 (5.7)	7.0 (7.5)	7.3 (7.6)	6.1 (6.4)	5.5 (5.8)	5.1 (5.4)	4.9 (5.1)
LO $\times 1.3$	6.3 (6.5)	5.7 (5.8)	7.3 (7.7)	7.5 (7.8)	6.3 (6.5)	5.7 (5.9)	5.3 (5.5)	5.0 (5.2)
$\mu\mu$ for $m_{\mu\mu} > 1.8 \text{ TeV}$								
LO	6.7 (6.5)	6.0 (5.8)	7.9 (7.6)	7.9 (7.7)	6.7 (6.5)	6.0 (5.9)	5.6 (5.5)	5.3 (5.2)
LO $\times 1.3$	6.8 (6.6)	6.1 (5.9)	8.1 (7.8)	8.1 (7.9)	6.8 (6.6)	6.2 (6.0)	5.7 (5.6)	5.4 (5.3)
Combined ee and $\mu\mu$ for $m_{\ell\ell} > 1.8 \text{ TeV}$								
LO	6.7 (6.8)	6.0 (6.0)	7.9 (8.0)	8.0 (8.0)	6.7 (6.8)	6.1 (6.1)	5.7 (5.7)	5.4 (5.4)
LO $\times 1.3$	6.9 (6.9)	6.1 (6.2)	8.2 (8.2)	8.2 (8.2)	6.9 (6.9)	6.2 (6.2)	5.8 (5.8)	5.5 (5.5)
Combined ee, $\mu\mu$, and $\gamma\gamma$ for $m_{\ell\ell} > 1.8 \text{ TeV}$ and $m_{\gamma\gamma} > 500 \text{ GeV}$								
LO	7.7 (7.5)	6.9 (6.7)	9.3 (8.9)	9.1 (8.9)	7.7 (7.5)	6.9 (6.8)	6.5 (6.3)	6.1 (6.0)

Table 2. Exclusion limits at 95% CL for the electron and muon channels, their combination, and the combination with the diphoton [10] analysis, in multiple parameter conventions of the ADD model. Signal model cross sections are calculated up to leading order and, where indicated by the appropriate label, a correction factor of 1.3 is applied. For each of the model parameters, the first value is the observed limit followed by the expected limit in parentheses.

comparison is not possible because the ATLAS limits are based on priors for Λ , whereas the limits reported here are based on a prior that is flat in cross section. For the ADD model, the results reported here are the first measurements at $\sqrt{s} = 13$ TeV in the dilepton final state. The combination with the CMS diphoton analysis yields the most sensitive results in nonhadronic final states to date.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NKFI (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (U.S.A.).

Individuals have received support from the Marie-Curie programme and the European Research Council and Horizon 2020 Grant, contract No. 675440 (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the “Excellence of Science — EOS” — be.h project n. 30820817; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Lendület (“Momentum”) Programme and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFI research grants 123842, 123959, 124845, 124850, and 125105 (Hungary); the Council of Science and Industrial Research, India; the HOMING PLUS programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus programme of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2015-0509 and the Programa Severo Ochoa del Principado de Asturias; the Thalís and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for

Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Welch Foundation, contract C-1845; and the Weston Havens Foundation (U.S.A.).

Open Access. This article is distributed under the terms of the Creative Commons Attribution License ([CC-BY 4.0](https://creativecommons.org/licenses/by/4.0/)), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited.

References

- [1] E. Eichten, I. Hinchliffe, K.D. Lane and C. Quigg, *Supercollider physics*, *Rev. Mod. Phys.* **56** (1984) 579 [[INSPIRE](#)].
- [2] N. Arkani-Hamed, S. Dimopoulos and G.R. Dvali, *The hierarchy problem and new dimensions at a millimeter*, *Phys. Lett. B* **429** (1998) 263 [[hep-ph/9803315](#)] [[INSPIRE](#)].
- [3] E. Eichten, K.D. Lane and M.E. Peskin, *New tests for quark and lepton substructure*, *Phys. Rev. Lett.* **50** (1983) 811 [[INSPIRE](#)].
- [4] PARTICLE DATA GROUP collaboration, *Review of particle physics*, *Phys. Rev. D* **98** (2018) 030001 [[INSPIRE](#)].
- [5] G.F. Giudice, R. Rattazzi and J.D. Wells, *Quantum gravity and extra dimensions at high-energy colliders*, *Nucl. Phys. B* **544** (1999) 3 [[hep-ph/9811291](#)] [[INSPIRE](#)].
- [6] J.L. Hewett, *Indirect collider signals for extra dimensions*, *Phys. Rev. Lett.* **82** (1999) 4765 [[hep-ph/9811356](#)] [[INSPIRE](#)].
- [7] T. Han, J.D. Lykken and R.-J. Zhang, *Kaluza-Klein states from large extra dimensions*, *Phys. Rev. D* **59** (1999) 105006 [[hep-ph/9811350](#)] [[INSPIRE](#)].
- [8] CMS collaboration, *Search for physics beyond the standard model in dilepton mass spectra in proton-proton collisions at $\sqrt{s} = 8$ TeV*, *JHEP* **04** (2015) 025 [[arXiv:1412.6302](#)] [[INSPIRE](#)].
- [9] CMS collaboration, *Search for high-mass resonances in dilepton final states in proton-proton collisions at $\sqrt{s} = 13$ TeV*, *JHEP* **06** (2018) 120 [[arXiv:1803.06292](#)] [[INSPIRE](#)].
- [10] CMS collaboration, *Search for physics beyond the standard model in high-mass diphoton events from proton-proton collisions at $\sqrt{s} = 13$ TeV*, *Phys. Rev. D* **98** (2018) 092001 [[arXiv:1809.00327](#)] [[INSPIRE](#)].
- [11] CMS collaboration, *Search for new physics in dijet angular distributions using proton-proton collisions at $\sqrt{s} = 13$ TeV and constraints on dark matter and other models*, *Eur. Phys. J. C* **78** (2018) 789 [[arXiv:1803.08030](#)] [[INSPIRE](#)].
- [12] ATLAS collaboration, *Search for contact interactions and large extra dimensions in the dilepton channel using proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, *Eur. Phys. J. C* **74** (2014) 3134 [[arXiv:1407.2410](#)] [[INSPIRE](#)].
- [13] ATLAS collaboration, *Search for new high-mass phenomena in the dilepton final state using 36fb^{-1} of proton-proton collision data at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *JHEP* **10** (2017) 182 [[arXiv:1707.02424](#)] [[INSPIRE](#)].
- [14] CMS collaboration, *The CMS experiment at the CERN LHC*, 2008 *JINST* **3** S08004 [[INSPIRE](#)].

- [15] CMS collaboration, *The CMS trigger system*, [2017 JINST 12 P01020](#) [[arXiv:1609.02366](#)] [[INSPIRE](#)].
- [16] CMS collaboration, *Search for narrow resonances in dilepton mass spectra in proton-proton collisions at $\sqrt{s} = 13$ TeV and combination with 8 TeV data*, *Phys. Lett. B* **768** (2017) 57 [[arXiv:1609.05391](#)] [[INSPIRE](#)].
- [17] CMS collaboration, *Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV*, [2015 JINST 10 P06005](#) [[arXiv:1502.02701](#)] [[INSPIRE](#)].
- [18] CMS collaboration, *Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV*, [2018 JINST 13 P06015](#) [[arXiv:1804.04528](#)] [[INSPIRE](#)].
- [19] P. Nason, *A new method for combining NLO QCD with shower Monte Carlo algorithms*, *JHEP* **11** (2004) 040 [[hep-ph/0409146](#)] [[INSPIRE](#)].
- [20] S. Frixione, P. Nason and C. Oleari, *Matching NLO QCD computations with parton shower simulations: the POWHEG method*, *JHEP* **11** (2007) 070 [[arXiv:0709.2092](#)] [[INSPIRE](#)].
- [21] S. Alioli, P. Nason, C. Oleari and E. Re, *A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX*, *JHEP* **06** (2010) 043 [[arXiv:1002.2581](#)] [[INSPIRE](#)].
- [22] S. Alioli, P. Nason, C. Oleari and E. Re, *NLO vector-boson production matched with shower in POWHEG*, *JHEP* **07** (2008) 060 [[arXiv:0805.4802](#)] [[INSPIRE](#)].
- [23] S. Frixione, P. Nason and G. Ridolfi, *A positive-weight next-to-leading-order Monte Carlo for heavy flavour hadroproduction*, *JHEP* **09** (2007) 126 [[arXiv:0707.3088](#)] [[INSPIRE](#)].
- [24] E. Re, *Single-top Wt-channel production matched with parton showers using the POWHEG method*, *Eur. Phys. J. C* **71** (2011) 1547 [[arXiv:1009.2450](#)] [[INSPIRE](#)].
- [25] NNPDF collaboration, *Parton distributions for the LHC Run II*, *JHEP* **04** (2015) 040 [[arXiv:1410.8849](#)] [[INSPIRE](#)].
- [26] T. Sjöstrand et al., *An introduction to PYTHIA 8.2*, *Comput. Phys. Commun.* **191** (2015) 159 [[arXiv:1410.3012](#)] [[INSPIRE](#)].
- [27] Y. Li and F. Petriello, *Combining QCD and electroweak corrections to dilepton production in the framework of the FEWZ simulation code*, *Phys. Rev. D* **86** (2012) 094034 [[arXiv:1208.5967](#)] [[INSPIRE](#)].
- [28] M. Botje et al., *The PDF4LHC Working Group Interim Recommendations*, [arXiv:1101.0538](#) [[INSPIRE](#)].
- [29] S. Alekhin et al., *The PDF4LHC Working Group Interim Report*, [arXiv:1101.0536](#) [[INSPIRE](#)].
- [30] J. Butterworth et al., *PDF4LHC recommendations for LHC Run II*, *J. Phys. G* **43** (2016) 023001 [[arXiv:1510.03865](#)] [[INSPIRE](#)].
- [31] A. Manohar, P. Nason, G.P. Salam and G. Zanderighi, *How bright is the proton? A precise determination of the photon parton distribution function*, *Phys. Rev. Lett.* **117** (2016) 242002 [[arXiv:1607.04266](#)] [[INSPIRE](#)].
- [32] D. Bourilkov, *Photon-induced background for dilepton searches and measurements in pp collisions at 13 TeV*, [arXiv:1606.00523](#) [[INSPIRE](#)].

- [33] D. Bourilkov, *Exploring the LHC landscape with dileptons*, [arXiv:1609.08994](#) [INSPIRE].
- [34] GEANT4 collaboration, GEANT4 — *a simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250 [INSPIRE].
- [35] M. Czakon and A. Mitov, *Top++: A program for the calculation of the top-pair cross-section at hadron colliders*, *Comput. Phys. Commun.* **185** (2014) 2930 [[arXiv:1112.5675](#)] [INSPIRE].
- [36] N. Kidonakis, *Two-loop soft anomalous dimensions for single top quark associated production with a W^- or H^-* , *Phys. Rev. D* **82** (2010) 054018 [[arXiv:1005.4451](#)] [INSPIRE].
- [37] R. Boughezal et al., *Color-singlet production at NNLO in MCFM*, *Eur. Phys. J. C* **77** (2017) 7 [[arXiv:1605.08011](#)] [INSPIRE].
- [38] J.M. Campbell, R.K. Ellis and W.T. Giele, *A multi-threaded version of MCFM*, *Eur. Phys. J. C* **75** (2015) 246 [[arXiv:1503.06182](#)] [INSPIRE].
- [39] J.M. Campbell, R.K. Ellis and C. Williams, *Vector boson pair production at the LHC*, *JHEP* **07** (2011) 018 [[arXiv:1105.0020](#)] [INSPIRE].
- [40] J.M. Campbell and R.K. Ellis, *Update on vector boson pair production at hadron colliders*, *Phys. Rev. D* **60** (1999) 113006 [[hep-ph/9905386](#)] [INSPIRE].
- [41] R.D. Ball et al., *Parton distributions with LHC data*, *Nucl. Phys. B* **867** (2013) 244 [[arXiv:1207.1303](#)] [INSPIRE].
- [42] J. Alwall et al., *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, *JHEP* **07** (2014) 079 [[arXiv:1405.0301](#)] [INSPIRE].
- [43] T. Ahmed et al., *NNLO QCD corrections to the Drell–Yan cross section in models of TeV-scale gravity*, *Eur. Phys. J. C* **77** (2017) 22 [[arXiv:1606.08454](#)] [INSPIRE].
- [44] CMS collaboration, *CMS luminosity measurements for the 2016 data taking period*, [CMS-PAS-LUM-17-001](#) (2017).
- [45] ATLAS and CMS collaborations and The LHC Higgs Combination Group, *Procedure for the LHC Higgs boson search combination in Summer 2011*, [CMS-NOTE-2011-005](#) (2011).
- [46] L. Moneta et al., *The RooStats project*, [PoS\(ACAT2010\)057](#) (2010) [[arXiv:1009.1003](#)] [INSPIRE].
- [47] J. Ott, THETA — *A framework for template-based modeling and inference*, 2010, <http://www-ekp.physik.uni-karlsruhe.de/~ott/theta/theta-auto>.

The CMS collaboration

Yerevan Physics Institute, Yerevan, Armenia

A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria

W. Adam, F. Ambrogio, E. Asilar, T. Bergauer, J. Brandstetter, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth¹, V.M. Ghete, J. Hrubec, M. Jeitler¹, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, H. Rohringer, J. Schieck¹, R. Schöffbeck, M. Spanring, D. Spitzbart, W. Waltenberger, J. Wittmann, C.-E. Wulz¹, M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus

V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, M. Pieters, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Université Libre de Bruxelles, Bruxelles, Belgium

D. Beghin, B. Bilin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, A.K. Kalsi, T. Lenzi, J. Luetic, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, Q. Wang

Ghent University, Ghent, Belgium

T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov², D. Poyraz, C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, A. Giammanco, G. Krintiras, V. Lemaitre, A. Magitteri, K. Piotrkowski, A. Saggio, M. Vidal Marono, P. Vischia, S. Wertz, J. Zobec

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

F.L. Alves, G.A. Alves, M. Correa Martins Junior, G. Correia Silva, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato³, E. Coelho, E.M. Da Costa, G.G. Da Silveira⁴, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, D. Matos Figueiredo, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote³, F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista ^a, Universidade Federal do ABC ^b, São Paulo, Brazil

S. Ahuja^a, C.A. Bernardes^a, L. Calligaris^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, P.G. Mercadante^b, S.F. Novaes^a, SandraS. Padula^a

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, A. Marinov, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria

A. Dimitrov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China

W. Fang⁵, X. Gao⁵, L. Yuan

Institute of High Energy Physics, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, S.M. Shaheen⁶, A. Spiezia, J. Tao, E. Yazgan, H. Zhang, S. Zhang⁶, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang

Tsinghua University, Beijing, China

Y. Wang

Universidad de Los Andes, Bogota, Colombia

C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, M.A. Segura Delgado

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia

B. Courbon, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, M. Roguljic, A. Starodumov⁷, T. Susa

University of Cyprus, Nicosia, Cyprus

M.W. Ather, A. Attikis, M. Kolosova, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

Charles University, Prague, Czech Republic

M. Finger⁸, M. Finger Jr.⁸

Escuela Politecnica Nacional, Quito, Ecuador

E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador

E. Carrera Jarrin

**Academy of Scientific Research and Technology of the Arab Republic of Egypt,
Egyptian Network of High Energy Physics, Cairo, Egypt**

S. Elgammal⁹, A. Ellithi Kamel¹⁰, A. Mohamed¹¹

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik,
M. Raidal, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

J. Havukainen, J.K. Heikkilä, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén,
K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen,
E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland

T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour,
A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, J. Malcles,
G. Negro, J. Rander, A. Rosowsky, M.Ö. Sahin, M. Titov

**Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université
Paris-Saclay, Palaiseau, France**

A. Abdulsalam¹², C. Amendola, I. Antropov, F. Beaudette, P. Busson, C. Charlot,
R. Granier de Cassagnac, I. Kucher, A. Lobanov, J. Martin Blanco, C. Martin Perez,
M. Nguyen, C. Ochando, G. Ortona, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan,
Y. Sirois, A.G. Stahl Leiton, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France

J.-L. Agram¹³, J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, V. Cherepanov, C. Collard,
E. Conte¹³, J.-C. Fontaine¹³, D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon,
P. Van Hove

**Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique
des Particules, CNRS/IN2P3, Villeurbanne, France**

S. Gadrat

**Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut
de Physique Nucléaire de Lyon, Villeurbanne, France**

S. Beauceron, C. Bernet, G. Boudoul, N. Chanon, R. Chierici, D. Contardo, P. Depasse,
H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde,
I.B. Laktineh, H. Lattaud, M. Lethuillier, L. Mirabito, S. Perries, A. Popov¹⁴, V. Sordini,
G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia

T. Toriashvili¹⁵

Tbilisi State University, Tbilisi, Georgia

Z. Tsamalaidze⁸

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, M.P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

A. Albert, D. Duchardt, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, S. Ghosh, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, T. Pook, M. Radziej, H. Reithler, M. Rieger, A. Schmidt, D. Teyssier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

G. Flügge, O. Hlushchenko, T. Kress, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl¹⁶

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, I. Babounikau, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, D. Bertsche, A.A. Bin Anuar, K. Borras¹⁷, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, T. Eichhorn, A. Elwood, E. Eren, E. Gallo¹⁸, A. Geiser, J.M. Grados Luyando, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, A. Lelek, T. Lenz, J. Leonard, K. Lipka, W. Lohmann¹⁹, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, J. Mnich, V. Myronenko, S.K. Pfitsch, D. Pitzl, A. Raspereza, P. Saxena, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, H. Tholen, O. Turkot, A. Vagnerini, M. Van De Klundert, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

University of Hamburg, Hamburg, Germany

R. Aggleton, S. Bein, L. Benato, A. Benecke, V. Blobel, T. Dreyer, A. Ebrahimi, E. Garutti, D. Gonzalez, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Kanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, D. Marconi, J. Multhaupt, M. Nedziela, C.E.N. Niemeyer, D. Nowatschin, A. Perieanu, A. Reimers, O. Rieger, C. Scharf, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, B. Vormwald, I. Zoi

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

M. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, B. Freund, M. Giffels, M.A. Harrendorf, F. Hartmann¹⁶, S.M. Heindl, U. Husemann, I. Katkov¹⁴, S. Kudella, S. Mitra, M.U. Mozer, Th. Müller, M. Musich, M. Plagge, G. Quast, K. Rabbertz,

M. Schröder, I. Shvetsov, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, C. Wöhrmann, R. Wolf

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

G. Anagnostou, G. Daskalakis, T. Gerasis, A. Kyriakis, D. Loukas, G. Paspalaki

National and Kapodistrian University of Athens, Athens, Greece

A. Agapitos, G. Karathanasis, P. Kontaxakis, A. Panagiotou, I. Papavergou, N. Saoulidou, E. Tziaferi, K. Vellidis

National Technical University of Athens, Athens, Greece

K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

University of Ioánnina, Ioánnina, Greece

I. Evangelou, C. Foudas, P. Giannios, P. Katsoulis, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F.A. Triantis, D. Tsitsonis

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

M. Bartók²⁰, M. Csanad, N. Filipovic, P. Major, M.I. Nagy, G. Pasztor, O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath²¹, Á. Hunyadi, F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi[†]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi²⁰, A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary

P. Raics, Z.L. Trocsanyi, B. Ujvari

Indian Institute of Science (IISc), Bangalore, India

S. Choudhury, J.R. Komaragiri, P.C. Tiwari

National Institute of Science Education and Research, HBNI, Bhubaneswar, India

S. Bahinipati²³, C. Kar, P. Mal, K. Mandal, A. Nayak²⁴, S. Roy Chowdhury, D.K. Sahoo²³, S.K. Swain

Panjab University, Chandigarh, India

S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, M. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, A. Mehta, K. Sandeep, S. Sharma, J.B. Singh, A.K. Viridi, G. Walia

University of Delhi, Delhi, India

A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, Ashok Kumar, S. Malhotra, M. Naimuddin, P. Priyanka, K. Ranjan, Aashaq Shah, R. Sharma

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

R. Bhardwaj²⁵, M. Bharti²⁵, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep²⁵, D. Bhowmik, S. Dey, S. Dutt²⁵, S. Dutta, S. Ghosh, M. Maity²⁶, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, A. Roy, G. Saha, S. Sarkar, T. Sarkar²⁶, M. Sharan, B. Singh²⁵, S. Thakur²⁵

Indian Institute of Technology Madras, Madras, India

P.K. Behera, A. Muhammad

Bhabha Atomic Research Centre, Mumbai, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, D.K. Mishra, P.K. Netrakanti, L.M. Pant, P. Shukla, P. Suggsetti

Tata Institute of Fundamental Research-A, Mumbai, India

T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, RavindraKumar Verma

Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, N. Sahoo

Indian Institute of Science Education and Research (IISER), Pune, India

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kotheekar, S. Pandey, A. Rane, A. Rastogi, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

S. Chenarani²⁷, E. Eskandari Tadavani, S.M. Etesami²⁷, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi, B. Safarzadeh²⁸, M. Zeinali

University College Dublin, Dublin, Ireland

M. Felcini, M. Grunewald

INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy

M. Abbrescia^{a,b}, C. Calabria^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c}, M. De Palma^{a,b}, A. Di Florio^{a,b}, F. Errico^{a,b}, L. Fiore^a, A. Gelmi^{a,b}, G. Iaselli^{a,c}, M. Ince^{a,b}, S. Lezki^{a,b}, G. Maggi^{a,c}, M. Maggi^a, G. Miniello^{a,b}, S. My^{a,b}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^a, A. Ranieri^a, G. Selvaggi^{a,b}, A. Sharma^a, L. Silvestris^a, R. Venditti^a, P. Verwilligen^a

INFN Sezione di Bologna ^a, Università di Bologna ^b, Bologna, Italy

G. Abbiendi^a, C. Battilana^{a,b}, D. Bonacorsi^{a,b}, L. Borgonovi^{a,b}, S. Braibant-Giacomelli^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, S.S. Chhibra^{a,b}, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, E. Fontanesi, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, F. Iemmi^{a,b}, S. Lo Meo^{a,29}, S. Marcellini^a, G. Masetti^a, A. Montanari^a, F.L. Navarria^{a,b}, A. Perrotta^a, F. Primavera^{a,b}, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, N. Tosi^a

INFN Sezione di Catania ^a, Università di Catania ^b, Catania, Italy

S. Albergo^{a,b}, A. Di Mattia^a, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

INFN Sezione di Firenze ^a, Università di Firenze ^b, Firenze, Italy

G. Barbagli^a, K. Chatterjee^{a,b}, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b},
G. Latino, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, L. Russo^{a,30}, G. Sguazzoni^a, D. Strom^a,
L. Viliani^a

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo

INFN Sezione di Genova ^a, Università di Genova ^b, Genova, Italy

F. Ferro^a, R. Mulargia^{a,b}, E. Robutti^a, S. Tosi^{a,b}

INFN Sezione di Milano-Bicocca ^a, Università di Milano-Bicocca ^b, Milano, Italy

A. Benaglia^a, A. Beschi^b, F. Brivio^{a,b}, V. Ciriolo^{a,b,16}, S. Di Guida^{a,b,16}, M.E. Dinardo^{a,b},
S. Fiorendi^{a,b}, S. Gennai^a, A. Ghezzi^{a,b}, P. Govoni^{a,b}, M. Malberti^{a,b}, S. Malvezzi^a,
D. Menasce^a, F. Monti, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b},
T. Tabarelli de Fatis^{a,b}, D. Zuolo^{a,b}

INFN Sezione di Napoli ^a, Università di Napoli 'Federico II' ^b, Napoli, Italy, Università della Basilicata ^c, Potenza, Italy, Università G. Marconi ^d, Roma, Italy

S. Buontempo^a, N. Cavallo^{a,c}, A. De Iorio^{a,b}, A. Di Crescenzo^{a,b}, F. Fabozzi^{a,c}, F. Fienga^a,
G. Galati^a, A.O.M. Iorio^{a,b}, L. Lista^a, S. Meola^{a,d,16}, P. Paolucci^{a,16}, C. Sciacca^{a,b},
E. Voevodina^{a,b}

INFN Sezione di Padova ^a, Università di Padova ^b, Padova, Italy, Università di Trento ^c, Trento, Italy

P. Azzi^a, N. Bacchetta^a, D. Bisello^{a,b}, A. Boletti^{a,b}, A. Bragagnolo, R. Carlin^{a,b},
P. Checchia^a, M. Dall'Osso^{a,b}, P. De Castro Manzano^a, T. Dorigo^a, U. Dosselli^a,
F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, S.Y. Hoh, S. Lacaprara^a, P. Lujan,
M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, J. Pazzini^{a,b}, M. Presilla^b, P. Ronchese^{a,b}, R. Rossin^{a,b},
F. Simonetto^{a,b}, A. Tiko, E. Torassa^a, M. Tosi^{a,b}, M. Zanetti^{a,b}, P. Zotto^{a,b}, G. Zumerle^{a,b}

INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy

A. Braghieri^a, A. Magnani^a, P. Montagna^{a,b}, S.P. Ratti^{a,b}, V. Re^a, M. Ressegotti^{a,b},
C. Riccardi^{a,b}, P. Salvini^a, I. Vai^{a,b}, P. Vitulo^{a,b}

INFN Sezione di Perugia ^a, Università di Perugia ^b, Perugia, Italy

M. Biasini^{a,b}, G.M. Bilei^a, C. Cecchi^{a,b}, D. Ciangottini^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b},
R. Leonardi^{a,b}, E. Manoni^a, G. Mantovani^{a,b}, V. Mariani^{a,b}, M. Menichelli^a, A. Rossi^{a,b},
A. Santocchia^{a,b}, D. Spiga^a

INFN Sezione di Pisa ^a, Università di Pisa ^b, Scuola Normale Superiore di Pisa ^c, Pisa, Italy

K. Androsov^a, P. Azzurri^a, G. Bagliesi^a, L. Bianchini^a, T. Boccali^a, L. Borrello,
R. Castaldi^a, M.A. Ciocci^{a,b}, R. Dell'Orso^a, G. Fedi^a, F. Fiori^{a,c}, L. Giannini^{a,c},
A. Giassi^a, M.T. Grippo^a, F. Ligabue^{a,c}, E. Manca^{a,c}, G. Mandorli^{a,c}, A. Messineo^{a,b},

F. Palla^a, A. Rizzi^{a,b}, G. Rolandi³¹, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verдини^a

INFN Sezione di Roma ^a, Sapienza Università di Roma ^b, Rome, Italy

L. Barone^{a,b}, F. Cavallari^a, M. Cipriani^{a,b}, D. Del Re^{a,b}, E. Di Marco^{a,b}, M. Diemoz^a, S. Gelli^{a,b}, E. Longo^{a,b}, B. Marzocchi^{a,b}, P. Meridiani^a, G. Organtini^{a,b}, F. Pandolfi^a, R. Paramatti^{a,b}, F. Preiato^{a,b}, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{a,b}

INFN Sezione di Torino ^a, Università di Torino ^b, Torino, Italy, Università del Piemonte Orientale ^c, Novara, Italy

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, N. Bartosik^a, R. Bellan^{a,b}, C. Biino^a, A. Cappati^{a,b}, N. Cartiglia^a, F. Cenna^{a,b}, S. Cometti^a, M. Costa^{a,b}, R. Covarelli^{a,b}, N. Demaria^a, B. Kiani^{a,b}, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, E. Monteil^{a,b}, M. Monteno^a, M.M. Obertino^{a,b}, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G.L. Pinna Angioni^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, R. Salvatico^{a,b}, K. Shchelina^{a,b}, V. Sola^a, A. Solano^{a,b}, D. Soldi^{a,b}, A. Staiano^a

INFN Sezione di Trieste ^a, Università di Trieste ^b, Trieste, Italy

S. Belforte^a, V. Candelise^{a,b}, M. Casarsa^a, F. Cossutti^a, A. Da Rold^{a,b}, G. Della Ricca^{a,b}, F. Vazzoler^{a,b}, A. Zanetti^a

Kyungpook National University, Daegu, Korea

D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, S. Sekmen, D.C. Son, Y.C. Yang

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea

H. Kim, D.H. Moon, G. Oh

Hanyang University, Seoul, Korea

B. Francois, J. Goh³², T.J. Kim

Korea University, Seoul, Korea

S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park, Y. Roh

Sejong University, Seoul, Korea

H.S. Kim

Seoul National University, Seoul, Korea

J. Almond, J. Kim, J.S. Kim, H. Lee, K. Lee, K. Nam, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

University of Seoul, Seoul, Korea

D. Jeon, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park

Sungkyunkwan University, Suwon, Korea

Y. Choi, C. Hwang, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania

V. Dudenas, A. Juodagalvis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

Z.A. Ibrahim, M.A.B. Md Ali³³, F. Mohamad Idris³⁴, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico

J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

H. Castilla-Valdez, E. De La Cruz-Burelo, M.C. Duran-Osuna, I. Heredia-De La Cruz³⁵, R. Lopez-Fernandez, J. Mejia Guisao, R.I. Rabadan-Trejo, M. Ramirez-Garcia, G. Ramirez-Sanchez, R. Reyes-Almanza, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

A. Morelos Pineda

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

S. Bheesette, P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

A. Ahmad, M. Ahmad, M.I. Asghar, Q. Hassan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, M. Szleper, P. Traczyk, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

K. Bunkowski, A. Byszk³⁶, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

M. Araujo, P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, J. Seixas, G. Strong, O. Toldaiev, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, A. Lanev, A. Malakhov, V. Matveev^{37,38}, P. Moisezenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

V. Golovtsov, Y. Ivanov, V. Kim³⁹, E. Kuznetsova⁴⁰, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, A. Shabanov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepenov, V. Stolin, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia

T. Aushev

National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia

M. Chadeeva⁴¹, D. Philippov, E. Popova, V. Rusinov

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin³⁸, M. Kirakosyan, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

A. Belyaev, E. Boos, V. Bunichev, M. Dubinin⁴², L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin

Novosibirsk State University (NSU), Novosibirsk, Russia

A. Barnyakov⁴³, V. Blinov⁴³, T. Dimova⁴³, L. Kardapol'tsev⁴³, Y. Skovpen⁴³

Institute for High Energy Physics of National Research Centre ‘Kurchatov Institute’, Protvino, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

National Research Tomsk Polytechnic University, Tomsk, Russia

A. Babaev, S. Baidali, V. Okhotnikov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

P. Adzic⁴⁴, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, J.A. Brochero Cifuentes, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M.S. Soares, A. Triossi

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain

J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, V. Rodríguez Bouza, S. Sanchez Cruz, J.M. Vizán García

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

University of Ruhuna, Department of Physics, Matara, Sri Lanka

N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Botta, E. Brondolin, T. Camporesi, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, G. Cucciati, D. d’Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, A. De Roeck, N. Deelen, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita⁴⁵, D. Fasanella, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, M. Gruchala, M. Guilbaud, D. Gulhan, J. Hegeman, C. Heidegger, V. Innocente, A. Jafari, P. Janot, O. Karacheban¹⁹, J. Kieseler, A. Kornmayer, M. Krammer¹, C. Lange, P. Lecoq, C. Lourenço, L. Malgeri, M. Mannelli, A. Massironi, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic⁴⁶, F. Moortgat, M. Mulders, J. Ngadiuba, S. Nourbakhsh, S. Orfanelli, L. Orsini, F. Pantaleo¹⁶, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabady, A. Racz, T. Reis, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas⁴⁷, A. Stakia, J. Steggemann, D. Treille, A. Tsiros, A. Vartak, V. Veckalns⁴⁸, M. Verzetti, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

L. Caminada⁴⁹, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, T. Rohe, S.A. Wiederkehr

ETH Zurich — Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland

M. Backhaus, L. Bäni, P. Berger, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T.A. Gómez Espinosa, C. Grab, D. Hits, T. Klijnsma, W. Lustermann, R.A. Manzoni, M. Marionneau, M.T. Meinhard, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pauss, G. Perrin, L. Perrozzi, S. Pigazzini, C. Reissel, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler⁵⁰, D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, S. Leontsinis, I. Neutelings, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, A. Zucchetta

National Central University, Chung-Li, Taiwan

T.H. Doan, R. Khurana, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.F. Liu, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand

B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey

A. Bat, F. Boran, S. Cerci⁵¹, S. Damarcekin, Z.S. Demiroglu, F. Dolek, C. Dozen, I. Dumanoglu, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos⁵², C. Isik, E.E. Kangal⁵³, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir⁵⁴, S. Ozturk⁵⁵, D. Sunar Cerci⁵¹, B. Tali⁵¹, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

B. Isildak⁵⁶, G. Karapinar⁵⁷, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

I.O. Atakisi, E. Gülmez, M. Kaya⁵⁸, O. Kaya⁵⁹, S. Ozkorucuklu⁶⁰, S. Tekten, E.A. Yetkin⁶¹

Istanbul Technical University, Istanbul, Turkey

M.N. Agaras, A. Cakir, K. Cankocak, Y. Komurcu, S. Sen⁶²

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine

B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

L. Levchuk

University of Bristol, Bristol, United Kingdom

F. Ball, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, D.M. Newbold⁶³, S. Paramesvaran, B. Penning, T. Sakuma, D. Smith, V.J. Smith, J. Taylor, A. Titterton

Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell, A. Belyaev⁶⁴, C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

Imperial College, London, United Kingdom

R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, D. Colling, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, G. Hall, G. Iles, T. James, M. Komm, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, J. Nash⁶⁵, A. Nikitenko⁷, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, G. Singh, M. Stoye, T. Strebler, S. Summers, A. Tapper, K. Uchida, T. Virdee¹⁶, N. Wardle, D. Winterbottom, S.C. Zenz

Brunel University, Uxbridge, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, A. Morton, I.D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, U.S.A.

K. Call, J. Dittmann, K. Hatakeyama, H. Liu, C. Madrid, B. McMaster, N. Pastika, C. Smith

Catholic University of America, Washington, DC, U.S.A.

R. Bartek, A. Dominguez

The University of Alabama, Tuscaloosa, U.S.A.

A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

Boston University, Boston, U.S.A.

D. Arcaro, T. Bose, D. Gastler, S. Girgis, D. Pinna, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Brown University, Providence, U.S.A.

G. Benelli, B. Burkle, X. Coubez, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan⁶⁶, K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, S. Sagir⁶⁷, R. Syarif, E. Usai, D. Yu

University of California, Davis, Davis, U.S.A.

R. Band, C. Brainerd, R. Breedon, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, W. Ko, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, D. Stolp, D. Taylor, K. Tos, M. Tripathi, Z. Wang, F. Zhang

University of California, Los Angeles, U.S.A.

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, S. Regnard, D. Saltzberg, C. Schnaible, V. Valuev

University of California, Riverside, Riverside, U.S.A.

E. Bouvier, K. Burt, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, W. Si, L. Wang, H. Wei, S. Wimpenny, B.R. Yates

University of California, San Diego, La Jolla, U.S.A.

J.G. Branson, P. Chang, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, D. Olivito, S. Padhi, M. Pieri, V. Sharma, S. Simon, M. Tadel, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara — Department of Physics, Santa Barbara, U.S.A.

N. Amin, R. Bhandari, C. Campagnari, M. Citron, V. Dutta, M. Franco Sevilla, L. Gouskos, R. Heller, J. Incandela, H. Mei, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, S. Wang, J. Yoo

California Institute of Technology, Pasadena, U.S.A.

D. Anderson, A. Bornheim, J.M. Lawhorn, N. Lu, H.B. Newman, T.Q. Nguyen, J. Pata, M. Spiropulu, J.R. Vlimant, R. Wilkinson, S. Xie, Z. Zhang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, U.S.A.

M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

University of Colorado Boulder, Boulder, U.S.A.

J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, U.S.A.

J. Alexander, J. Chaves, Y. Cheng, J. Chu, A. Datta, K. Mcdermott, N. Mirman, J.R. Patterson, D. Quach, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Fermi National Accelerator Laboratory, Batavia, U.S.A.

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, C. Pena, O. Prokofyev, G. Rakness, F. Ravera, A. Reinsvold, L. Ristori, A. Savoy-Navarro⁶⁸, B. Schneider, E. Sexton-Kennedy,

A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck

University of Florida, Gainesville, U.S.A.

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, L. Cadamuro, A. Carnes, D. Curry, R.D. Field, S.V. Gleyzer, B.M. Joshi, J. Konigsberg, A. Korytov, K.H. Lo, P. Ma, K. Matchev, G. Mitselmakher, D. Rosenzweig, K. Shi, D. Sperka, J. Wang, S. Wang, X. Zuo

Florida International University, Miami, U.S.A.

Y.R. Joshi, S. Linn

Florida State University, Tallahassee, U.S.A.

A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, C. Schiber, R. Yohay

Florida Institute of Technology, Melbourne, U.S.A.

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, M. Rahmani, T. Roy, M. Saunders, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, U.S.A.

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, C. Mills, M.B. Tonjes, N. Varelas, H. Wang, X. Wang, Z. Wu, J. Zhang

The University of Iowa, Iowa City, U.S.A.

M. Alhusseini, B. Bilki⁶⁹, W. Clarida, K. Dilsiz⁷⁰, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul⁷¹, Y. Onel, F. Ozok⁷², A. Penzo, C. Snyder, E. Tiras, J. Wetzel

Johns Hopkins University, Baltimore, U.S.A.

B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, W.T. Hung, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao

The University of Kansas, Lawrence, U.S.A.

A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, A. Bylinkin, J. Castle, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, C. Rogan, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang

Kansas State University, Manhattan, U.S.A.

S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi

Lawrence Livermore National Laboratory, Livermore, U.S.A.

F. Rebassoo, D. Wright

University of Maryland, College Park, U.S.A.

A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, S. Nabili, F. Ricci-Tam, M. Seidel, Y.H. Shin, A. Skuja, S.C. Tonwar, K. Wong

Massachusetts Institute of Technology, Cambridge, U.S.A.

D. Abercrombie, B. Allen, V. Azzolini, A. Baty, G. Bauer, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, C. McGinn, C. Mironov, S. Narayanan, X. Niu, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

University of Minnesota, Minneapolis, U.S.A.

A.C. Benvenuti[†], R.M. Chatterjee, A. Evans, P. Hansen, J. Hiltbrand, Sh. Jain, S. Kalafut, M. Krohn, Y. Kubota, Z. Lesko, J. Mans, R. Rusack, M.A. Wadud

University of Mississippi, Oxford, U.S.A.

J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, U.S.A.

E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, F. Golf, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

State University of New York at Buffalo, Buffalo, U.S.A.

A. Godshalk, C. Harrington, I. Iashvili, A. Kharchilava, C. Mclean, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, U.S.A.

G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, G. Madigan, D.M. Morse, T. Orimoto, A. Tishelman-charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, U.S.A.

S. Bhattacharya, J. Bueghly, O. Charaf, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, U.S.A.

R. Bucci, N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, K. Lannon, W. Li, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko³⁷, M. Planer, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

The Ohio State University, Columbus, U.S.A.

J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, C. Hill, W. Ji, T.Y. Ling, W. Luo, B.L. Winer

Princeton University, Princeton, U.S.A.

S. Cooperstein, P. Elmer, J. Hardenbrook, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, S. Kwan, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, J. Salfeld-Nebgen, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, U.S.A.

S. Malik, S. Norberg

Purdue University, West Lafayette, U.S.A.

A. Barker, V.E. Barnes, S. Das, L. Gutay, M. Jones, A.W. Jung, A. Khatiwada, B. Mahakud, D.H. Miller, N. Neumeister, C.C. Peng, S. Piperov, H. Qiu, J.F. Schulte, J. Sun, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, U.S.A.

T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, U.S.A.

Z. Chen, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, Arun Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, W. Shi, Z. Tu, A. Zhang

University of Rochester, Rochester, U.S.A.

A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, E. Ranken, P. Tan, R. Taus

Rutgers, The State University of New Jersey, Piscataway, U.S.A.

B. Chiarito, J.P. Chou, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen

University of Tennessee, Knoxville, U.S.A.

A.G. Delannoy, J. Heideman, G. Riley, S. Spanier

Texas A&M University, College Station, U.S.A.

O. Bouhali⁷³, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁷⁴, S. Luo, D. Marley, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, U.S.A.

N. Akchurin, J. Damgov, F. De Guio, P.R. Duderov, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Vanderbilt University, Nashville, U.S.A.

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, J.D. Ruiz Alvarez, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij, Q. Xu

University of Virginia, Charlottesville, U.S.A.

M.W. Arenton, P. Barria, B. Cox, R. Hirosky, M. Joyce, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, U.S.A.

R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

University of Wisconsin — Madison, Madison, WI, U.S.A.

J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, I. De Bruyn, L. Dodd, B. Gomber⁷⁵,
M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, K. Long,
R. Loveless, T. Ruggles, A. Savin, V. Sharma, N. Smith, W.H. Smith, N. Woods

†: Deceased

- 1: Also at Vienna University of Technology, Vienna, Austria
- 2: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- 3: Also at Universidade Estadual de Campinas, Campinas, Brazil
- 4: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
- 5: Also at Université Libre de Bruxelles, Bruxelles, Belgium
- 6: Also at University of Chinese Academy of Sciences, Beijing, China
- 7: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 8: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 9: Now at British University in Egypt, Cairo, Egypt
- 10: Now at Cairo University, Cairo, Egypt
- 11: Also at Zewail City of Science and Technology, Zewail, Egypt
- 12: Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia
- 13: Also at Université de Haute Alsace, Mulhouse, France
- 14: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- 15: Also at Tbilisi State University, Tbilisi, Georgia
- 16: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 17: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- 18: Also at University of Hamburg, Hamburg, Germany
- 19: Also at Brandenburg University of Technology, Cottbus, Germany
- 20: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
- 21: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 22: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
- 23: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
- 24: Also at Institute of Physics, Bhubaneswar, India
- 25: Also at Shoolini University, Solan, India
- 26: Also at University of Visva-Bharati, Santiniketan, India
- 27: Also at Isfahan University of Technology, Isfahan, Iran
- 28: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 29: Also at Italian National Agency For New Technologies, Energy And Sustainable Economic Development, Bologna, Italy
- 30: Also at Università degli Studi di Siena, Siena, Italy
- 31: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 32: Also at Kyunghee University, Seoul, Korea
- 33: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
- 34: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
- 35: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- 36: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- 37: Also at Institute for Nuclear Research, Moscow, Russia

- 38: Now at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
- 39: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 40: Also at University of Florida, Gainesville, U.S.A.
- 41: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 42: Also at California Institute of Technology, Pasadena, U.S.A.
- 43: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- 44: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 45: Also at INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy
- 46: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 47: Also at National and Kapodistrian University of Athens, Athens, Greece
- 48: Also at Riga Technical University, Riga, Latvia
- 49: Also at Universität Zürich, Zurich, Switzerland
- 50: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
- 51: Also at Adiyaman University, Adiyaman, Turkey
- 52: Also at Istanbul Aydin University, Istanbul, Turkey
- 53: Also at Mersin University, Mersin, Turkey
- 54: Also at Piri Reis University, Istanbul, Turkey
- 55: Also at Gaziosmanpasa University, Tokat, Turkey
- 56: Also at Ozyegin University, Istanbul, Turkey
- 57: Also at Izmir Institute of Technology, Izmir, Turkey
- 58: Also at Marmara University, Istanbul, Turkey
- 59: Also at Kafkas University, Kars, Turkey
- 60: Also at Istanbul University, Faculty of Science, Istanbul, Turkey
- 61: Also at Istanbul Bilgi University, Istanbul, Turkey
- 62: Also at Hacettepe University, Ankara, Turkey
- 63: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 64: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 65: Also at Monash University, Faculty of Science, Clayton, Australia
- 66: Also at Bethel University, St. Paul, U.S.A.
- 67: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- 68: Also at Purdue University, West Lafayette, U.S.A.
- 69: Also at Beykent University, Istanbul, Turkey
- 70: Also at Bingol University, Bingol, Turkey
- 71: Also at Sinop University, Sinop, Turkey
- 72: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 73: Also at Texas A&M University at Qatar, Doha, Qatar
- 74: Also at Kyungpook National University, Daegu, Korea
- 75: Also at University of Hyderabad, Hyderabad, India